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Modulation of Cloud Optical Properties by Vertical Circulations Associated With a Jet Streak Exit Region: The November 26 FIRE Cirrus Case Study

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1. Introduction

The period from 18 UTC 26 November 1991 to roughly 23 UTC 26 November 1991 has become a focal case study of the FIRE Cirrus-II field campaign. The middle and upper tropospheric cloud data that were collected have allowed FIRE scientists to learn a great deal about the morphological structure and microphysical and radiative characteristics of the mid-latitude cirrus that occurred during that time. An important component of this effort is determining the synoptic scale forcing that existed during this time. By forcing, we mean the coupling between the background vertical air motions and the large scale moisture budget that initiated and maintained cirrus cloud in the study region. Defining the synoptic scale forcing is one of the stated scientific objectives of the FIRE program.

It is also necessary, from the standpoint of model validation, that the vertical motions and large scale moisture budget of this case study be derived directly from observations i.e. independent of model-based data assimilation. We consider it important that the models used to simulate the observed cloud fields begin with the correct dynamics and that the dynamics be in the right place for the right reasons.

We have combined hourly Wind Profiler Demonstration Network data (Chadwick et al, 1985) with rawinsonde data processed at full vertical resolution to create objective analyses of the synoptic scale fields. Using diagnostics derived from the objectively analyzed data and bulk cloud optical properties determined from geostationary satellite data, we will infer interactions between the large scale forcing and the bulk cloud optical properties.

2. The November 26th Case Study

The middle and upper tropospheric cloud band that was sampled during the local afternoon of 26 November 1991 was closely coupled to the synoptic scale dynamics embedded in the exit region of a strong northwesterly jet stream. The jet extended from a ridge in the northwestern United States southeastward into the Texas Panhandle. A jet streak of 63 m s^{-1} was propagating southeastward near the flow inflection point in eastern Colorado. Immediately downstream of the jet core, a difluent trough axis extended from eastern Texas northward into the Dakotas. Analysis of the geopotential height field (not shown) shows that the trough axis had a well defined southeast-northwest tilt. This situation bears strong resemblance to a classic description of an upper jet-front system propagating through a synoptic scale baroclinic wave presented by Shapiro (1983) and Keyser and Shapiro (1987). This stage of development is marked by barotropic amplification through the tilt in the height field and by baroclinic amplification indicated by the weak cold advection in the northwesterly flow (Keyser and Shapiro, 1987). The amplification process is displayed quite markedly by examining the evolution of the dynamics between 18 UTC and 21 UTC. Fig. 1 shows vertical east-west cross sections of relative vorticity at 18 and 21 UTC. The cross sections extend from the jet core in southeastern Colorado across the trough axis north of the Kansas-Oklahoma border and into the difluent zone in western Missouri. The vorticity pattern shows a region of cyclonic vorticity extending through the depth of the troposphere and situated from the jet core eastward into the difluent trough with maximum amplitude near 10 km. The vorticity pattern bears a striking resemblance to that found in mobile upper tropospheric troughs (Sanders, 1988; Whitaker and Barcilon, 1992).

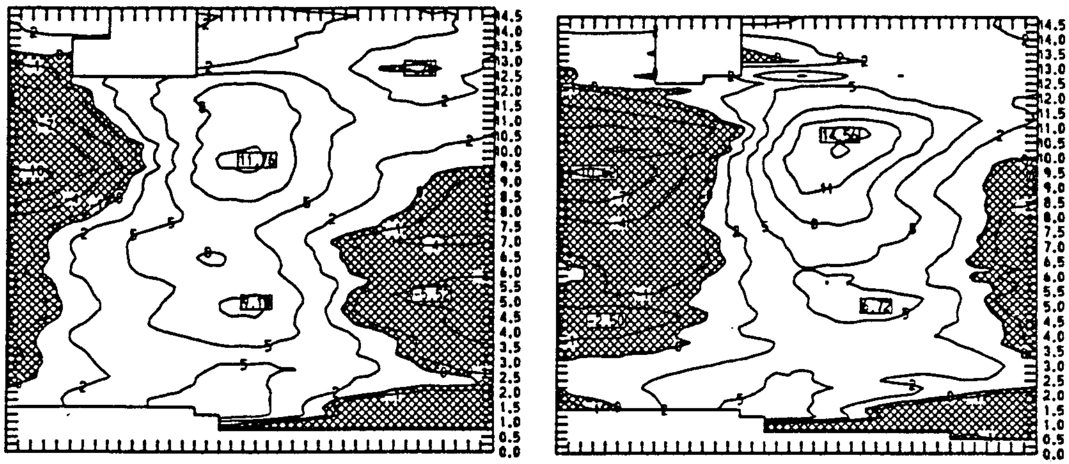

Fig. 1. Cross sections of the vertical component of the relative vorticity for a) 18 UTC 26 Nov. 91 and b) 21 UTC 26 Nov. 91. The cross sections extend in an east west line from south-central Colorado to southwestern Missouri. Units are in 10^{-5} s^{-1} and negative values are shaded.

The evolution of the vorticity pattern associated with the jet-trough system is clearly evident. The entire pattern appears to progress eastward during the three hour period. The amplitude of the disturbance appears to decrease between 4 and 6 km while a significant amplification is noted between 8 and 12 km. The negative vorticity values in the flanking migratory ridges show little change aside from an eastward progression during the period.

The vertical velocity was calculated as a residual from the first law of thermodynamics assuming adiabatic flow. Results at 6.5 km are shown in Fig. 2. At 18 UTC, weak large scale ascent is diagnosed in a band that extends southwestward from a local maximum in southwestern Iowa. At 21 UTC the center of uplift in southwestern Iowa decreases slightly in intensity. Elsewhere, amplification of the pattern is diagnosed. This includes the ascent zone as well as the region of strong subsidence centered on the Kansas-Nebraska border. The upward vertical motion more than doubles over most of eastern Oklahoma with the center of rising motion over the Red River showing evidence of eastward propagation.

The response of the cloud shield to the synoptic scale forcing can be seen by examining Fig. 3 which shows the high cloud visible optical depth (Minnis, 1990) at 18 UTC and 21 UTC. At 18 UTC the high clouds with the largest optical depths were associated with the center of rising motion over southwestern Iowa. A thick band of cirrus extended southwestward into central Kansas with optical depths exceeding 11 along the central portion of the cloud band. Thin cirrus extended southward into Oklahoma. By 21 UTC optical depths all along the cloud band showed a significant response to the evolving vertical motion pattern. This is most evident over Oklahoma. The eastward propagation of the southern portions of the cloud band are clearly evident. We find good correlation between the increasing optical depths in Oklahoma and the increasing vertical motions at 6.5 km. The increase in optical depths over southwestern Iowa are associated with sharply larger upward motion between 7 and 10 km (not shown).

3. Conclusions

The evolution of the cloud system extensively observed on 26 November can be seen as a response to vertical circulations associated with synoptic scale forcing. As the rapidly advancing jet streak passed the flow inflection point after 18 UTC, the system became predisposed to large scale amplification through the orientation of the trough axis and cold air advection. The strong gradient in velocity insured that parcels exiting the jet were strongly ageostrophic as they passed into the difluent trough.

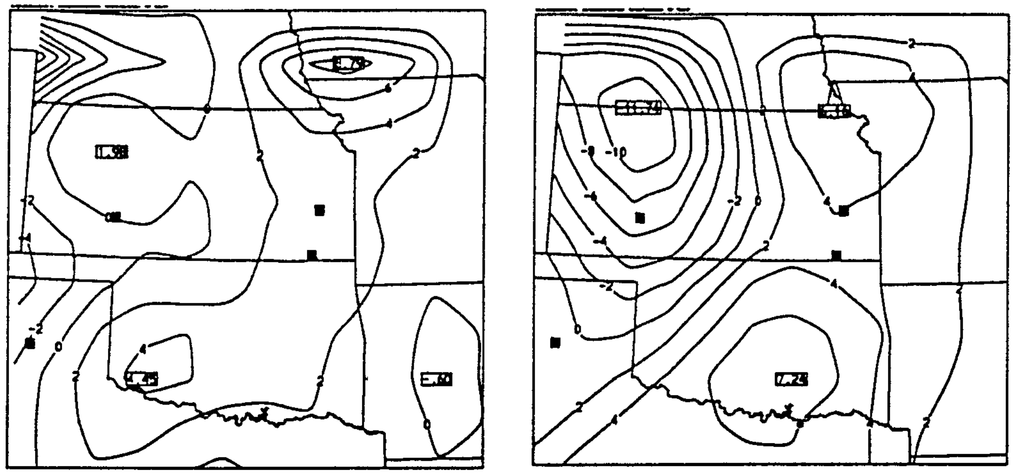

Fig. 2. Adiabatic vertical velocity at 6.5 km for a) 18 UTC 26 Nov. 91 and b) 21 UTC 26 Nov. 91. Contours are in cm s^{-1}

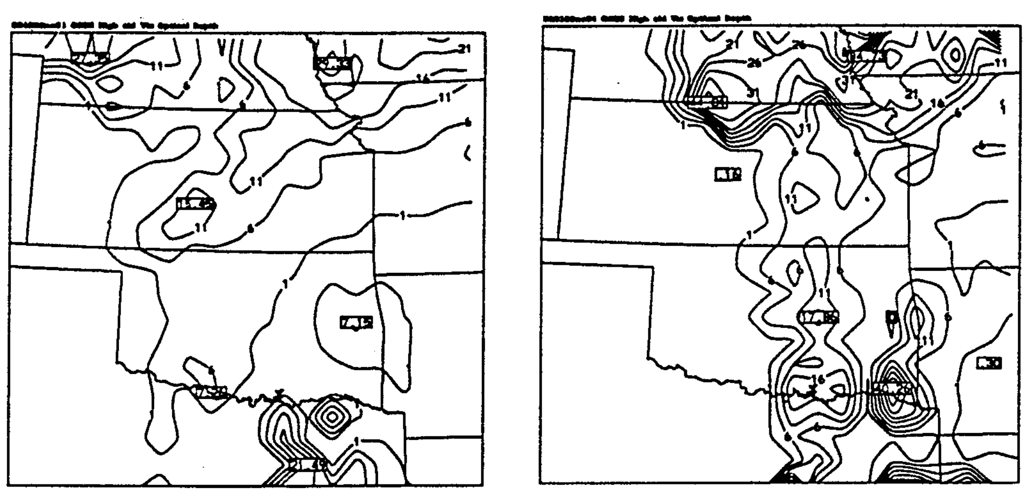

Fig. 3. High cloud visible optical depth determined from geostationary satellite data. a) 18 UTC 26 Nov. 1991, b) 21 UTC 26 Nov. 1991.

This contention is supported by kinematic analysis of wind profiler data that shows increasing upper tropospheric divergence during this period. The influence of trajectory curvature likely played an important role in the rather sudden amplification of the vertical motion pattern and concomitant modulation of the cloud optical properties. As shown by Cammas and Ramond (1989), advection of trajectory curvature can significantly enhance the vertical circulations that exist in curved jet flows.

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References

Available upon request.